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Computation of Turbulent Flow in a Rotating Pipe using an Elliptic Blending Reynolds Stress Model

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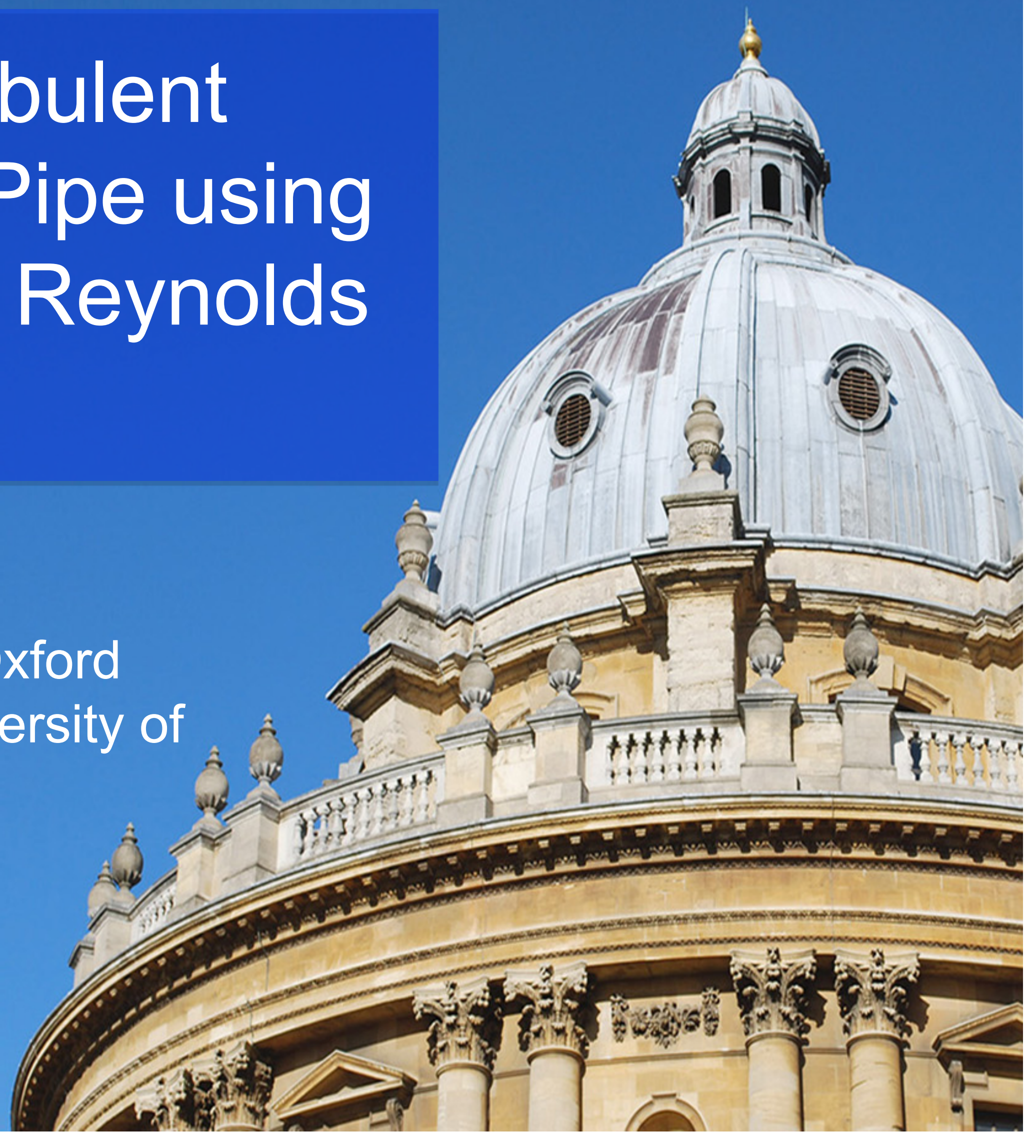

AMS Seminar Series
NASA Ames Research Center 05/07/2016

- Introduction & Motivation
- Turbulence Models
- OpenFOAM Verification & Validation
- Rotating pipe
    - Test-Case setup
    - Results
- Conclusions

Introduction

- Computational Fluid Dynamics (CFD) and High-Performance Computing (HPC) have transformed the engineering design process
- Many question whether **RANS** methods are becoming a thing of the past

Should we still be focusing on **RANS**?

Examples

LES / Hybrid RANS-LES require large grids but the hit is the temporal resolution

- Many examples of sectors who value rapid turn-around time
  - **Formula 1** – new car required every 2 weeks
  - **Classified special projects** – limit on the size of the cluster because of security

Turn-around time

1000's Design iterations

Formula 1 example

CFD Process

CAD → Preprocessing → Simulation on HPC

	Simulation
Mesh Size	120 million
Runtime	4.5 hrs
HPC Cores	192
Data	30GB

- 20 engineers x 3 simulations per day 60
- ~11,000 cores utilized
- 2TB per day, every day

Back of an envelope calculations, but broadly correct

	RANS	Hybrid RANS-LES
Mesh Size	80 million	5 **Billion**
Meshing Time (unstructured)	1.5 **hrs**	2 days
Solver Time	3 **hrs**	28 days
HPC Cores	128	8192
Post-Processing (forces,streamlines etc)	30 mins	360 mins

Hybrid RANS-LES time estimates

- Assuming 0.2mm smallest cell with $40ms^{-1}$, time step = $0.0001/40=5e^{-6}$
- 25 flow-throughs required (2m car). $0.05/2.5e^{-6}$=10,000x25= **250,000** time steps.
- Assume 10s per iteration on **8192** cores (industrial scaling)=**28.5 days**
- Post process the > 2TB data per run. **0.5days? Storage??**

Total time from Design to Result:
RANS: 5hrs (3-8% error when its working well, but depends on lengthy mesh optimization and solver optimization)
Hybrid RANS-LES: 30 days (1-3% error depend on many factors, underlying RANS model, inflow conditions, near-wall resolution!)

Formula 1

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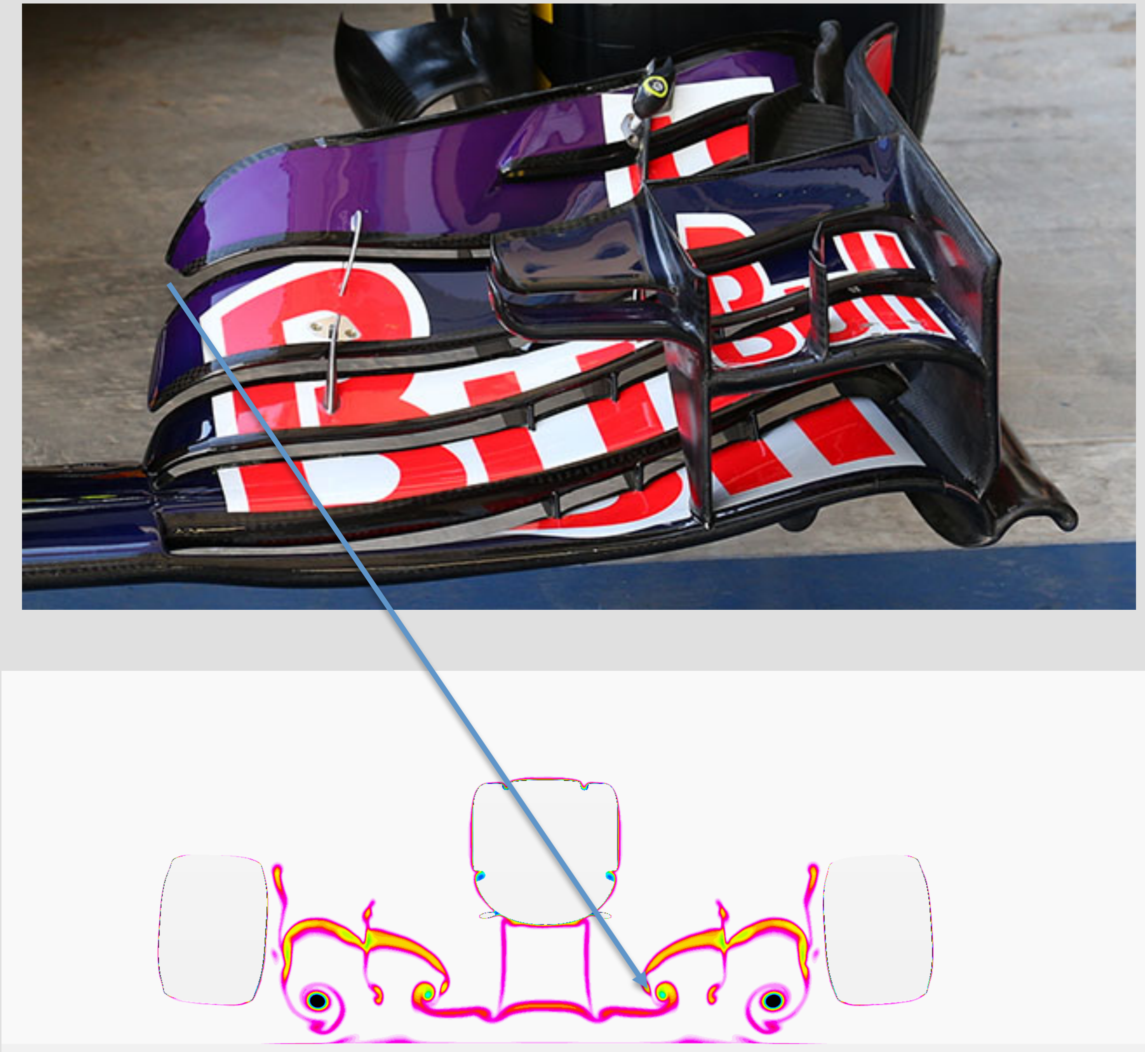

Formula 1

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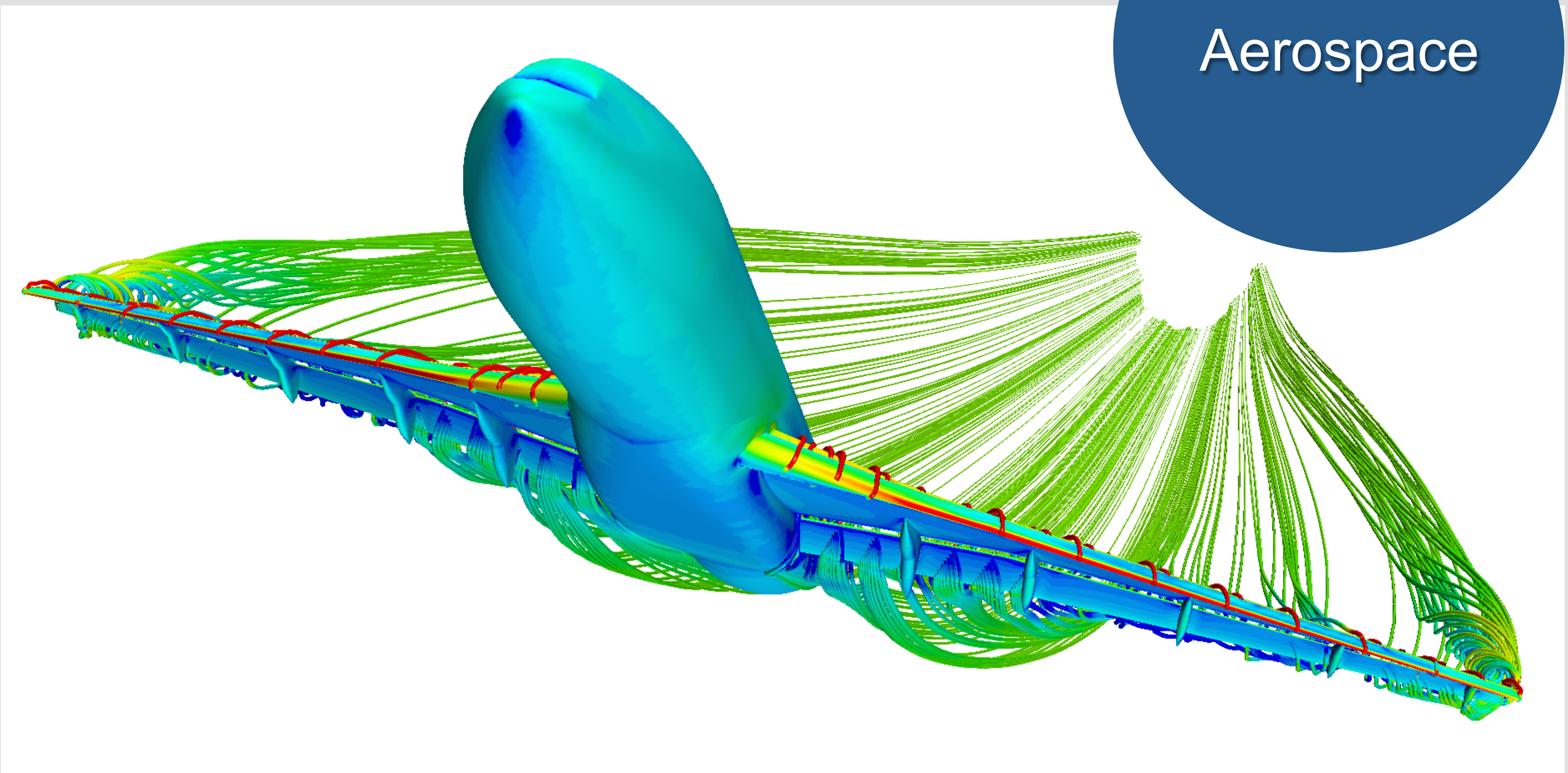
Rotation/Curvature

Aerospace



Defense

Motivation - Verification

- Verifying and developing turbulence models implementations requires grid convergence
- Grid convergence not possible on full complex geometries without > 1000 cores and > 1 billion cells
- Thus we need simple test cases – goal of NASA Turbulence Modelling Resource Site (TMR)

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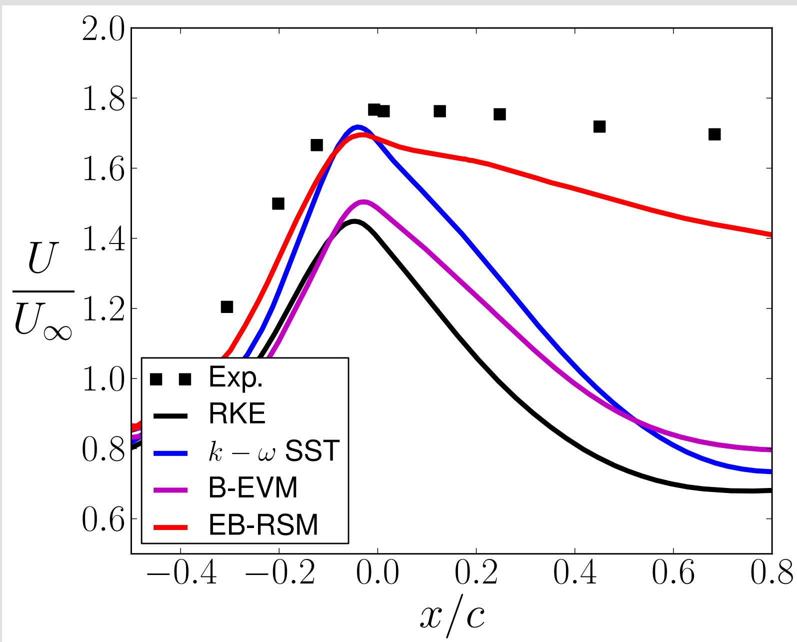
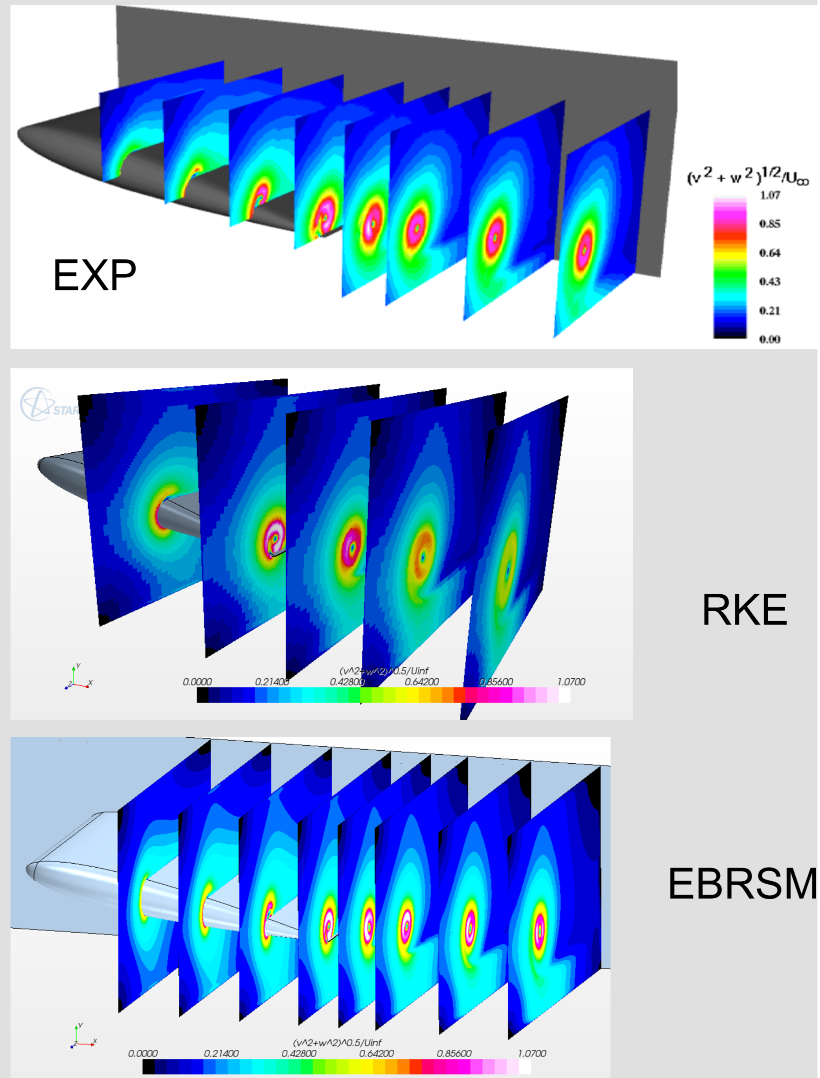
NACA0012 Wing tip

- Good example of aerospace flow (wing-tip vortices)
- Re=4 million
- 16 million cells example





With the correct model, which includes the right physics (i.e RSM) it is possible to capture the flow correctly.

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NACA0012 Wing tip

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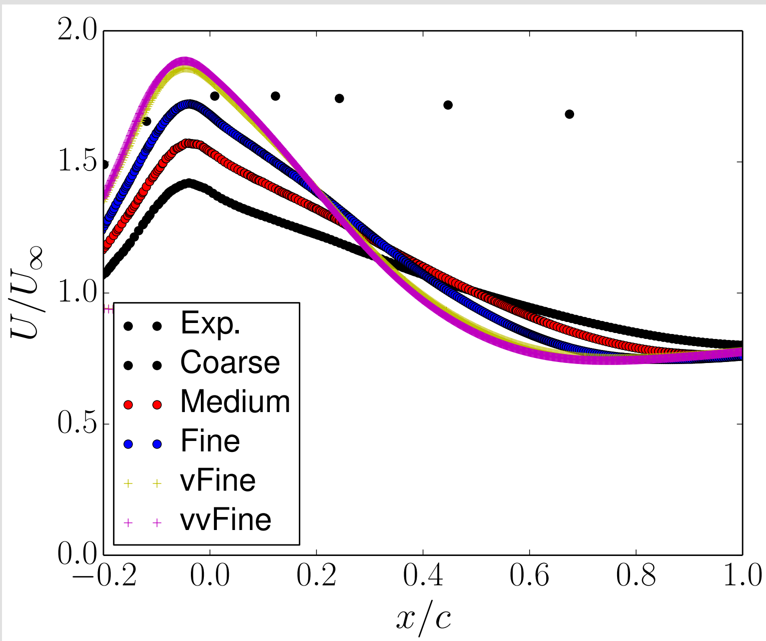
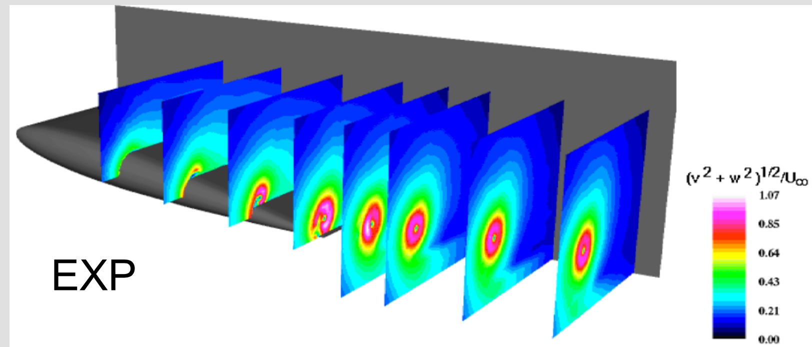
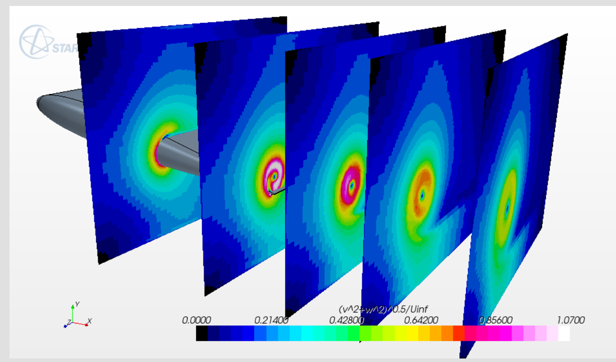
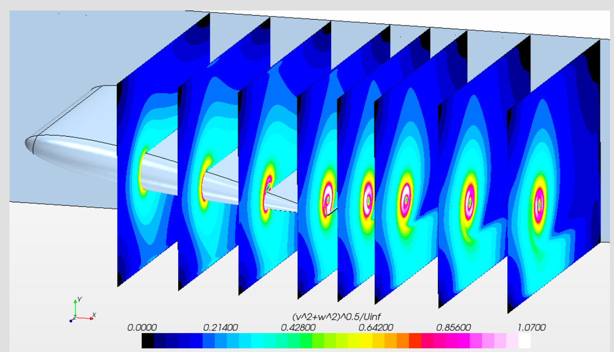
- Good example of aerospace flow (wing-tip vortices)
- Re=4 million
- Mesh convergence by 80 million cells







RKE



EBRSM

With the correct model, which includes the right physics (i.e RSM) it is possible to capture the flow correctly.

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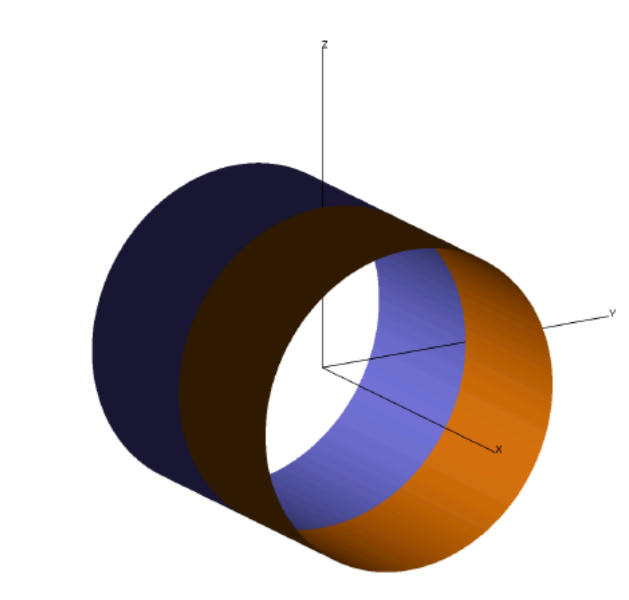
Rotating pipe

- Experimentally studied by a number of groups
- Stationary pipe of 100D (D=0.06m)
- Followed by Rotating pipe of 50D (also 200D for longer pipe)
- Swirling level: $N=W/U_0$
- W=wall rotating velocity
- U_0 = Velocity at the pipe axis



Rotating pipe

- Re_tau=875
- Two distinct regions:
  - 20-40D – turbulence suppression – stabilizing effect of rotation
  - 50-150D – saturation region where statistics reach a constant value

With increasing N, move towards a laminar profile

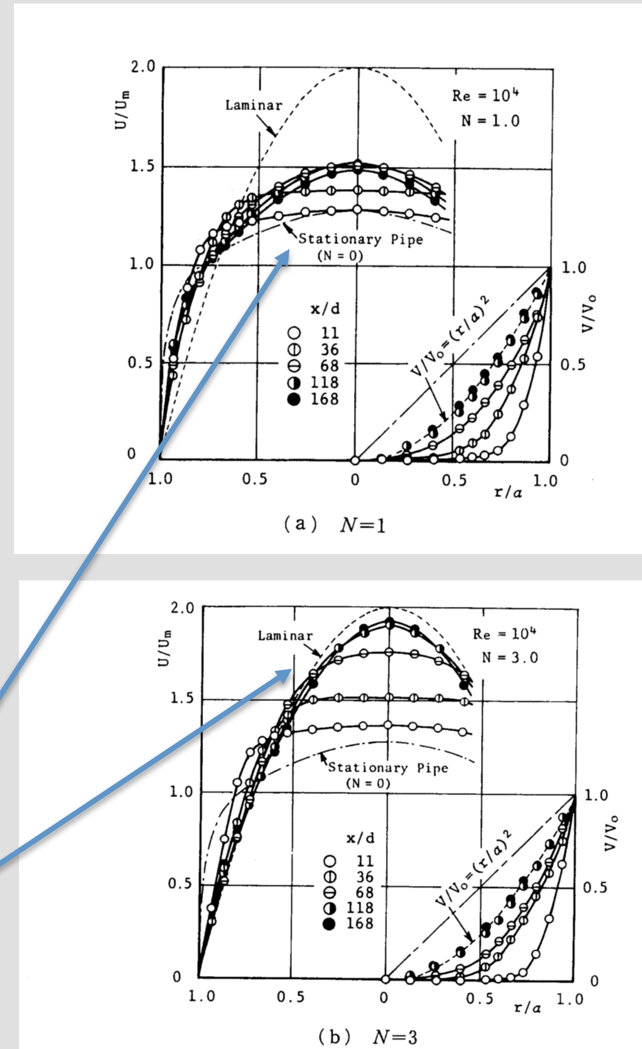


Fig. 2 Changes in velocity profiles along the pipe

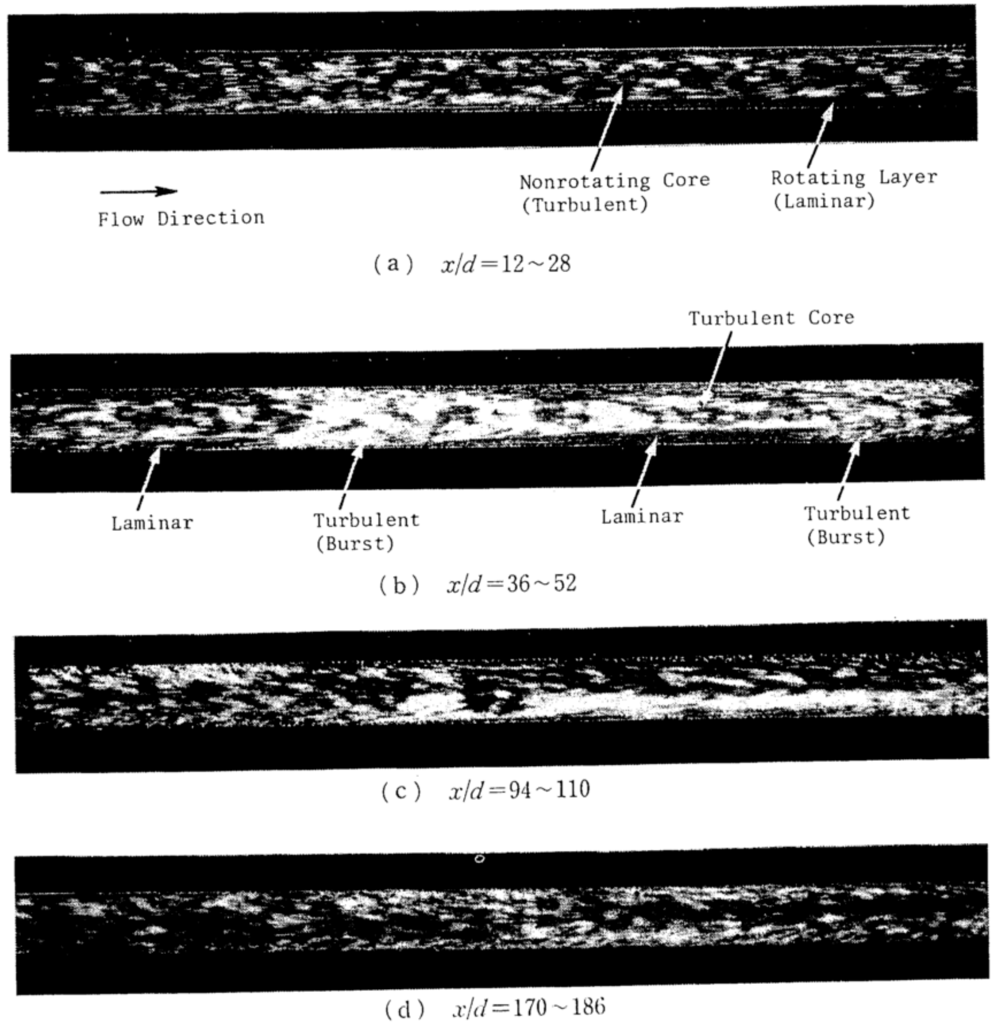
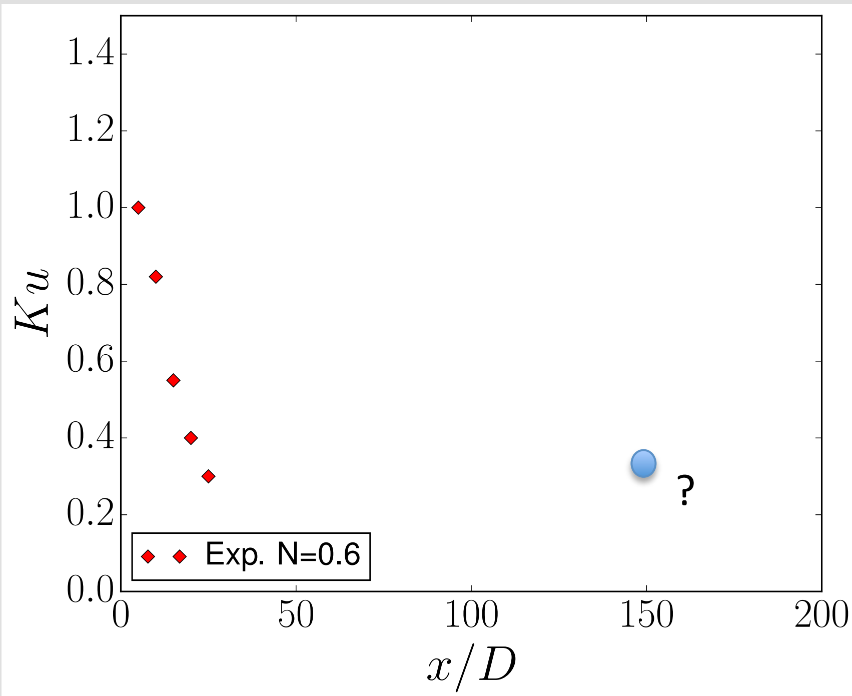


Fig. 6 Flow visualization ($Re=10^4$, $N=1$)

NISHIBORI, K., KIKUYAMA, K., & MURAKAMI, M. (1987). Laminarization of turbulent flow in the inlet region of an axially rotating pipe. *JSME International Journal*, *30*(260), 255–262. doi:10.1299/jsme1987.30.255



Lack of consistent data for long pipe

Ku- damping coefficient – ratio of Reynolds stress (Ku – uu) at stationary and rotating section

Previous work

- Number of CFD studies, at various rotation rates and Reynolds numbers
- Mixed conclusions, but typically”
    - RSM better than standard eddy-viscosity models
    - Rotation correction is typically needed – for eddy-viscosity models and also RSM (length-scale equation)
    - Importance of turbulent diffusion model

Turbulence Models

- K-omega SST Model - as per original reference

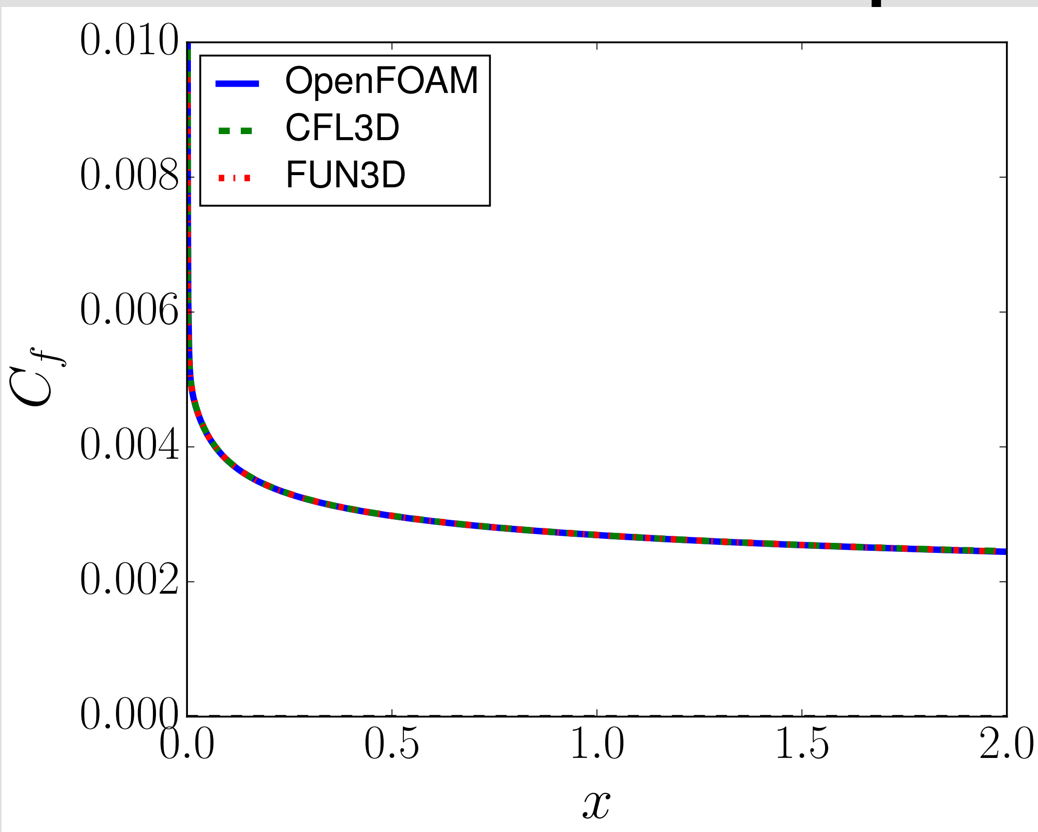
- Spalart-Allmaras – as per original reference

- Elliptic Blending RSM with homogeneous dissipation equation (Hanjalic + Jakirlic)

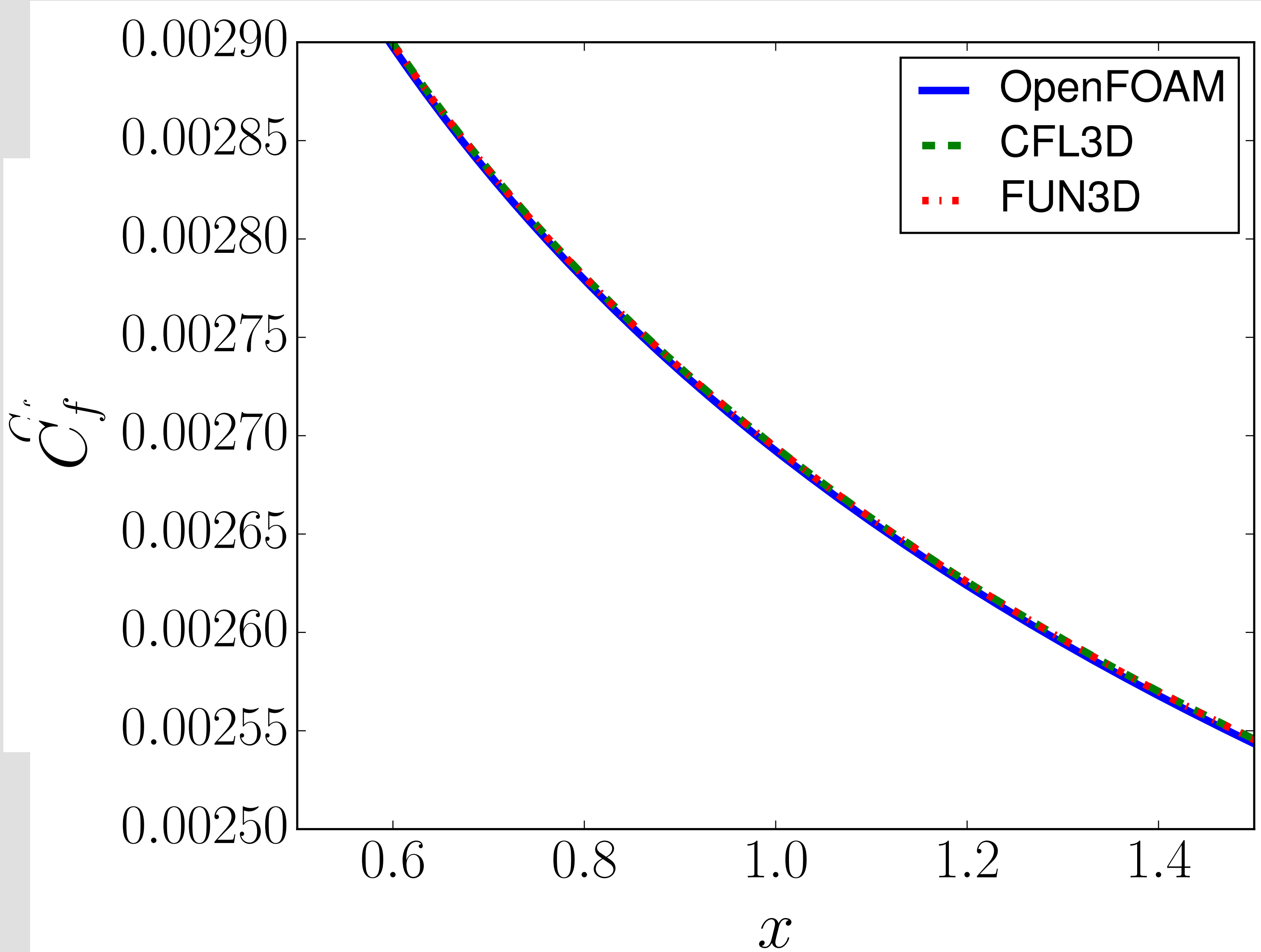
Important to establish that the SA/SST are correctly implemented in OpenFOAM and of the same form as other codes

- ZPG Flat Plate
- NACA0012
- Bump in a channel (not shown here)
- 2D hump (not shown here)

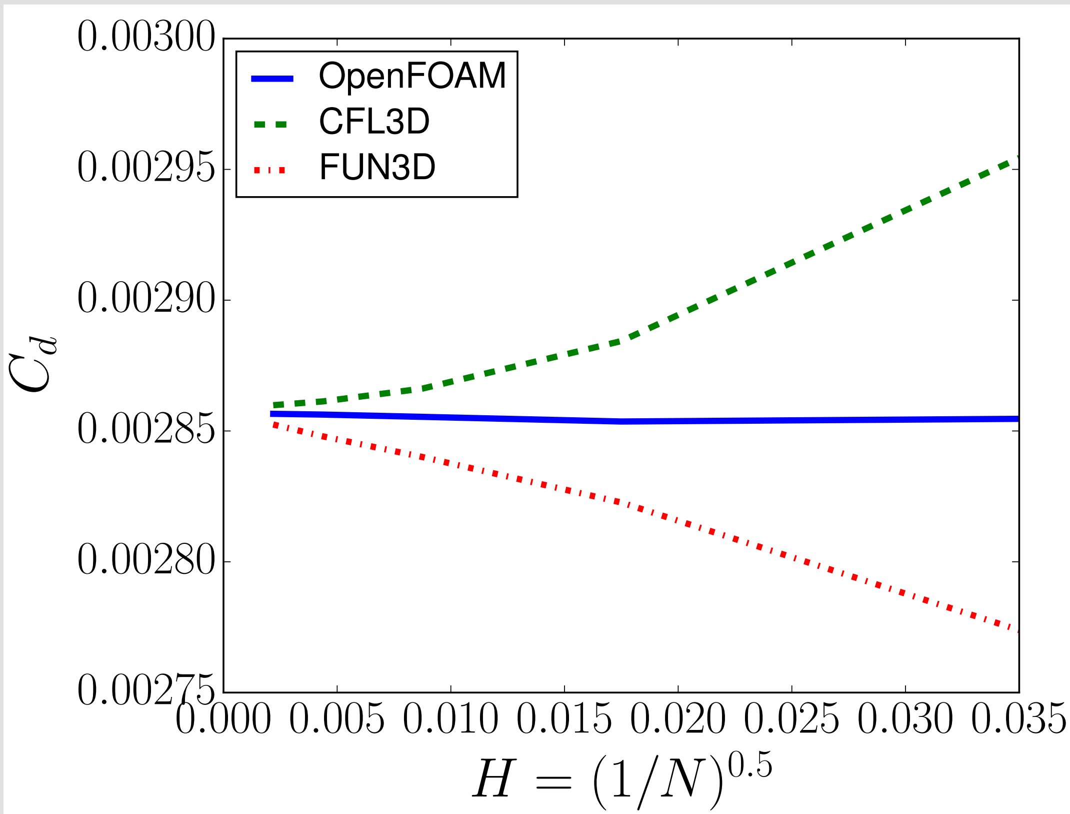
Flat Plate – compressible - SA



- 545x385 mesh from NASA TMR
- M=0.2
- Re=5x10^6
- Compressible steady-state
- Second order upwind for momentum + 1st order upwind for turbulence (to match CFL3D)
- Inlet: Turbulent viscosity ratio = 3

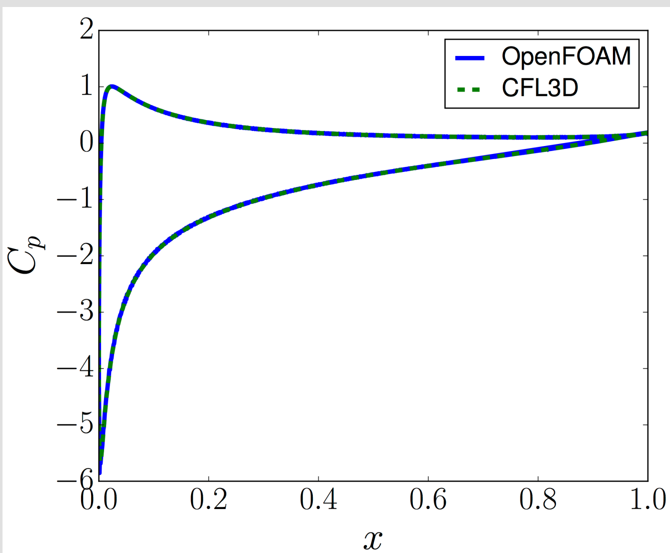

0.00290
0.00285
0.00280
0.00275
0.00270
0.00265
0.00260
0.00255
0.00250
C_f
0.6
0.8
1.0
1.2
1.4
x
OpenFOAM
CFL3D
FUN3D

Flat Plate – compressible - SA



NACA0012 – 10deg - SA

	Cl	Cd
OpenFOAM	1.08986	0.0121
CFL3D	1.0909	0.0123
FUN3D	1.0983	
NTS	1.0891	



- 897x257 mesh from NASA TMR
- M=0.15
- Re=6x10^6
- Compressible steady-state
- Second order upwind for momentum + 1st order upwind for turbulence (to match CFL3D)
- Inlet: Turbulent viscosity ratio = 3

$EB - RSM - \varepsilon_h$

$$\frac{\partial \tau_{ij}}{\partial t} + \bar{u}_j \frac{\partial \tau_{ij}}{\partial x_j} = P_{ij} + \Phi^*_{ij} - \varepsilon^h_{ij} + \frac{\partial}{\partial x_k}\left[\left(0.5\nu\delta_{kl} + C_k \frac{k}{\varepsilon^h}\tau_{kl}\right)\frac{\partial \tau_{ij}}{\partial x_l}\right]$$

$$\Phi^*_{ij} = (1 - f_\alpha)\Phi^w_{ij} + f_\alpha \Phi^h_{ij},$$

$$f_\alpha = \alpha^3$$

$$\alpha - L_d^2 \nabla^2 \alpha = 1.$$

$$\Phi^w_{ij} = -5\frac{\varepsilon^h}{k}\left(\tau_{ik}n_j n_k + \tau_{jk}n_i n_k - \frac{1}{2}\tau_{kl}n_k n_l\left(n_i n_j + \delta_{ij}\right)\right),$$

Manceau et al. (2001) simplified the full elliptic relaxation method of Durbin (1993)

Blends a near-wall formulation of the Pressure-Strain and Dissipation with a homogeneous model away from the wall (e.g SSG/LRR) to obtain correct asymptotic

$EB - RSM - \varepsilon_h$

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$EB - RSM - \varepsilon_h$

$$\frac{\partial \varepsilon^h}{\partial t} + \overline{u}_j \frac{\partial \varepsilon^h}{\partial x_j} = C_{\varepsilon 1} P \frac{\varepsilon^h}{k} - C_{\varepsilon 2} F_{rc} f_\varepsilon \frac{\tilde{\varepsilon}^h \varepsilon^h}{k} + E_\varepsilon + \frac{\partial}{\partial x_k}\left[\left(0.5 \nu \delta_{kl} + C_\varepsilon \frac{k}{\varepsilon^h} \tau_{kl}\right) \frac{\partial \varepsilon^h}{\partial x_l}\right],$$

$$E_\varepsilon = 2 C_{\varepsilon 3} \nu \frac{k^2}{\varepsilon^h} (1 - \alpha) \left(\frac{\partial^2 \overline{u}_i}{\partial x_k \partial x_k} \right)^2,$$

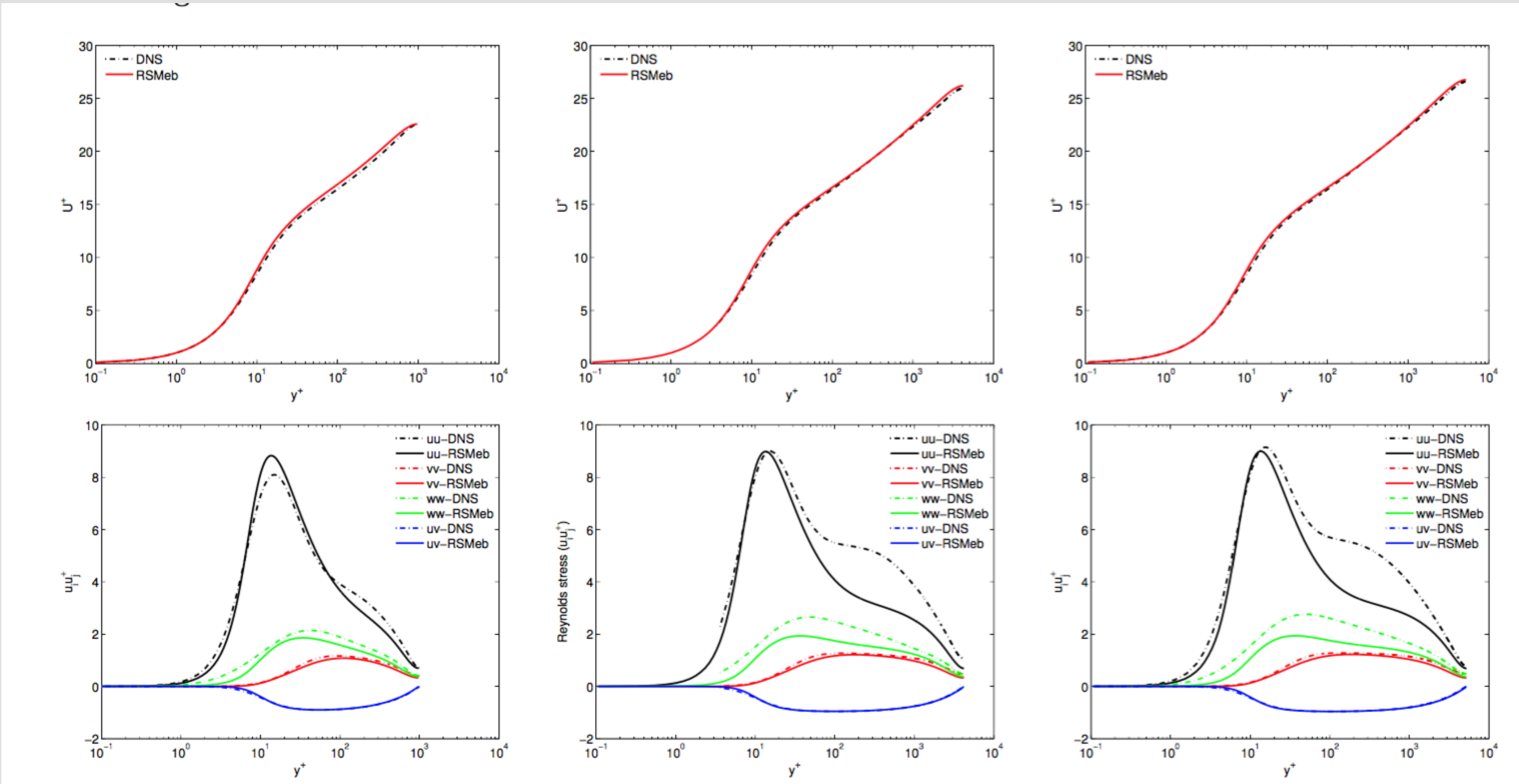
$$\tilde{\varepsilon}^h = \varepsilon^h - \nu \left(\frac{\partial \sqrt{k}}{\partial n} \right)^2.$$

Stoellinger et al. (2015) incorporated the homogenous dissipation rate equation of Hanjalic & Jakirlic (2002)

Term by term modelling approach based upon DNS to provide improved prediction

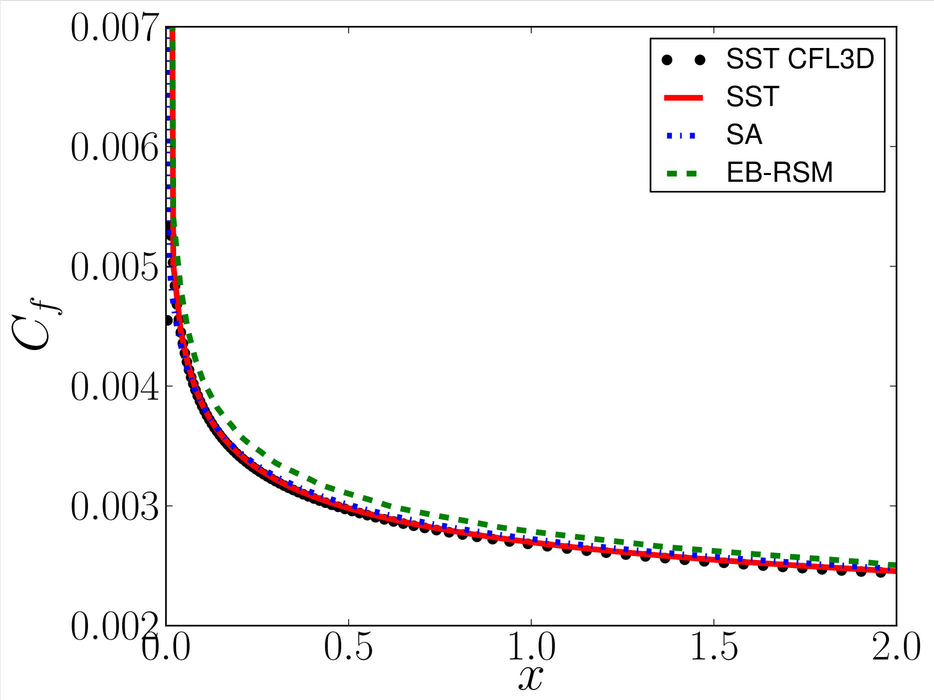
Full details in paper and original references

Re_tau=1000 Re_tau=4200 Re_tau=5200



- Stoellinger et al (2015) demonstrated performance on channel flow, periodic hills, NACA0012
- Same subroutines used in this work

Flat Plate



- 545x385 mesh from NASA TMR
- M=0.2
- Re=5x10^6
- Incompressible steady-state
- Second order upwind for momentum + 1st order upwind for turbulence (to match CFL3D)
- Inlet: Turbulent viscosity ratio = 3

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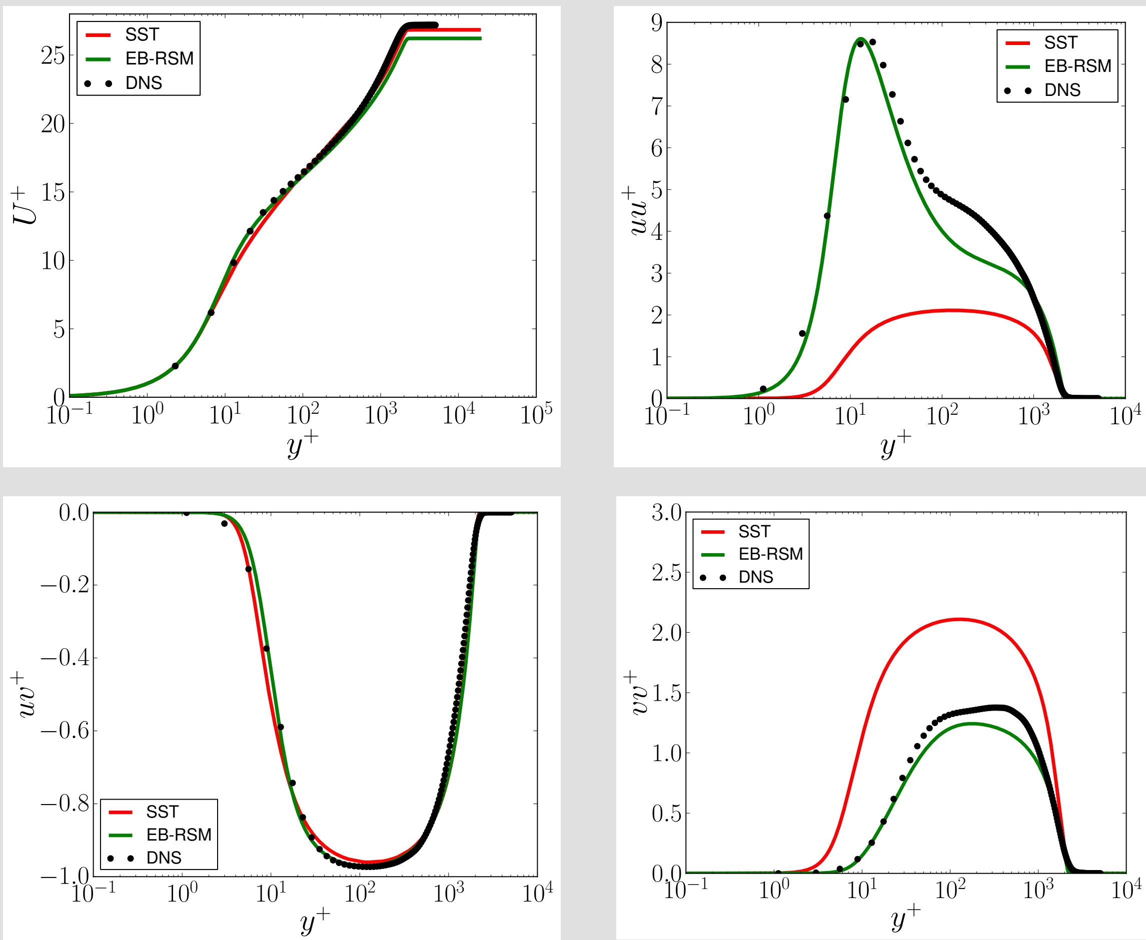
Flat Plate

J.A. Sillero, J. Jimenez, R.D. Moser "One-point statistics for turbulent wall-bounded flows at Reynolds numbers up to \delta^+\approx2000" Phys. Fluids 25, 105102, 3 October 2013



DNS data:

ZPG at Re_Theta=6650

http://torroja.dmt.upm.es/turbdata/blayers/high_re/

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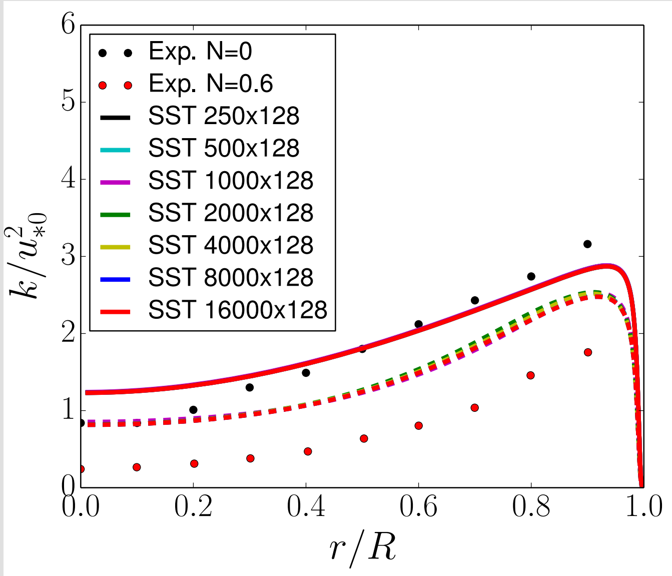
Case setup

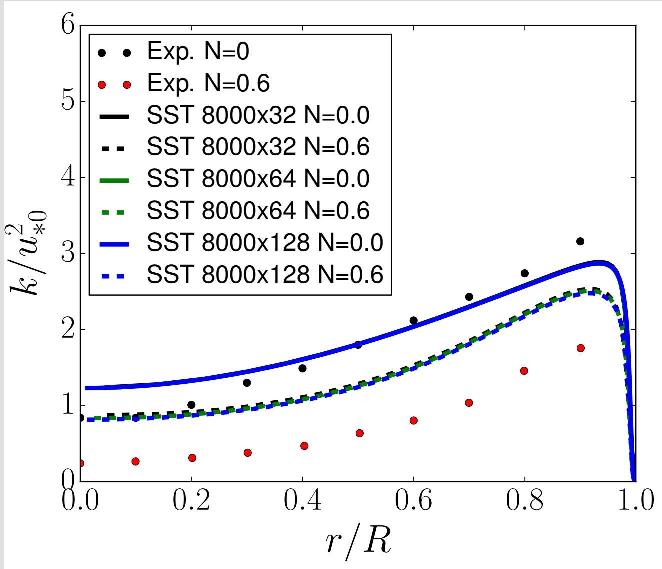
Rotating pipe

- OpenFoam
- Incompressible steady-state solver
- Asymmetric slice
- Second order upwind scheme for both turbulence and momentum
- Inlet velocity tuned to match **Re_tau=875**

Meshing

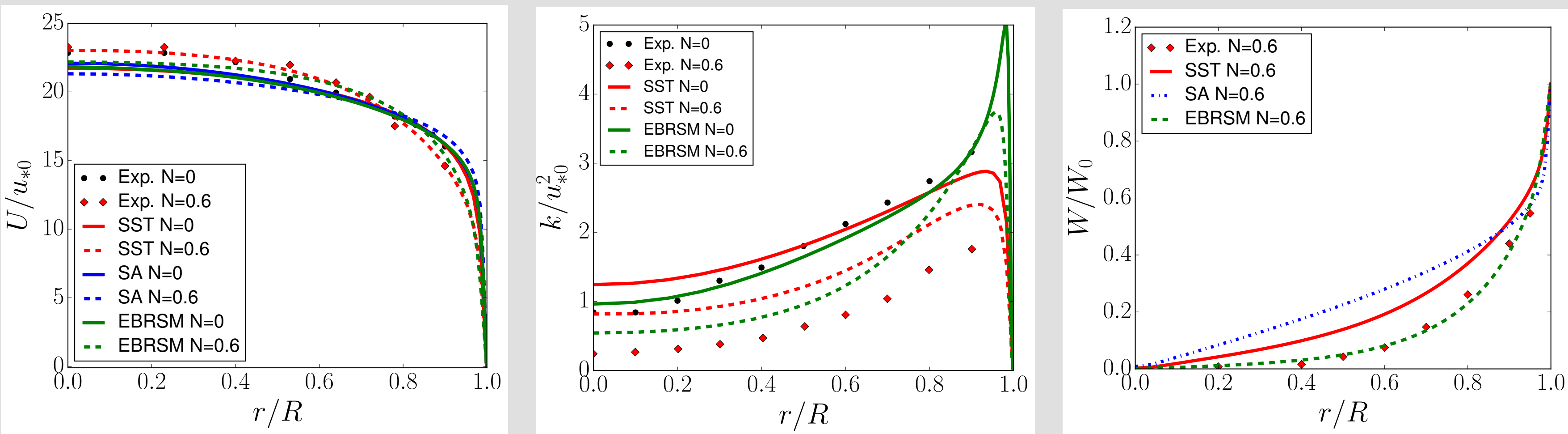
- Mesh convergence study undertaken
- Showed little sensitivity to the grid, although depends on how you stretch from the wall. RSM had numerical instabilities below 32 cells in the radial direction (too large stretching)





Results

Results

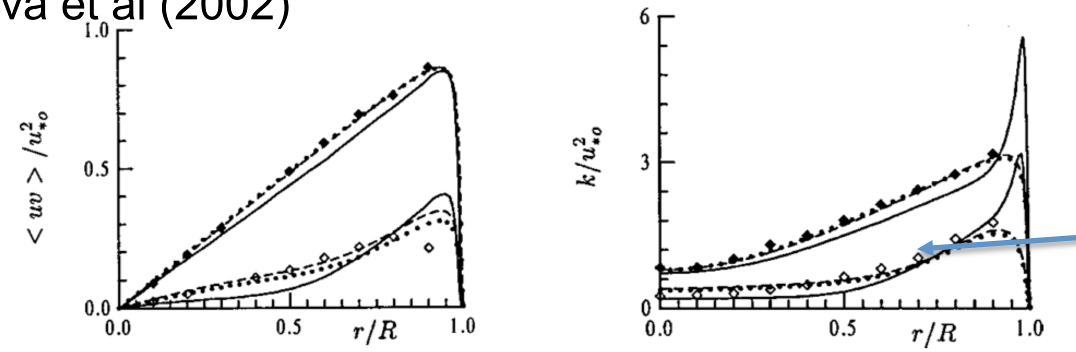


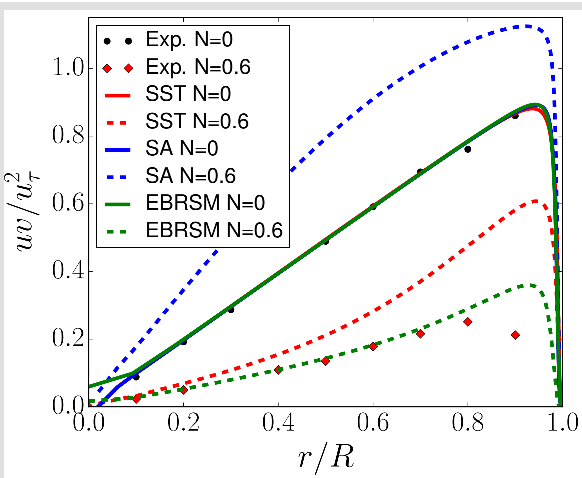
N=0 is at X/D=-10 - fully developed stationary pipe flow
N=0.6 is at X/D=25 – turbulent suppression region

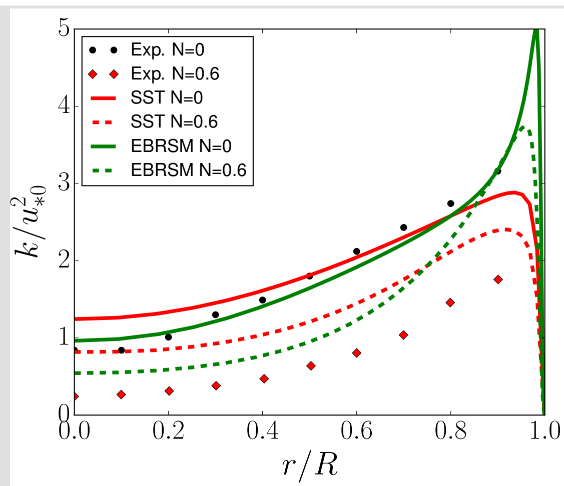
- Turbulence suppression is clearly observed
- SA model predicts the wrong trend (vorticity production keeps growing)
- SST/RSM show correct trend but underpredict the suppresion
- Results agree to within 2% of Mike Olsen (OVERFLOW)

Results

Poroseva et al (2002)



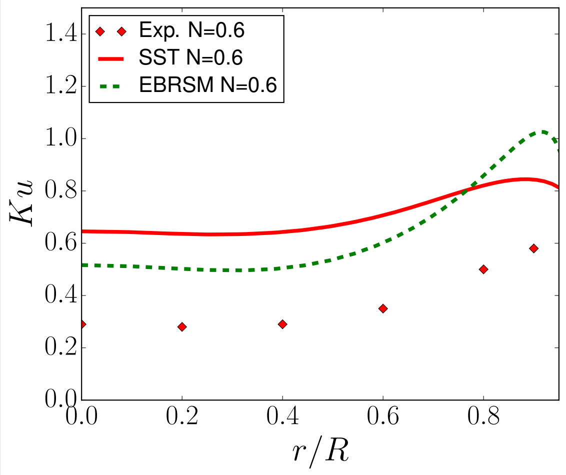


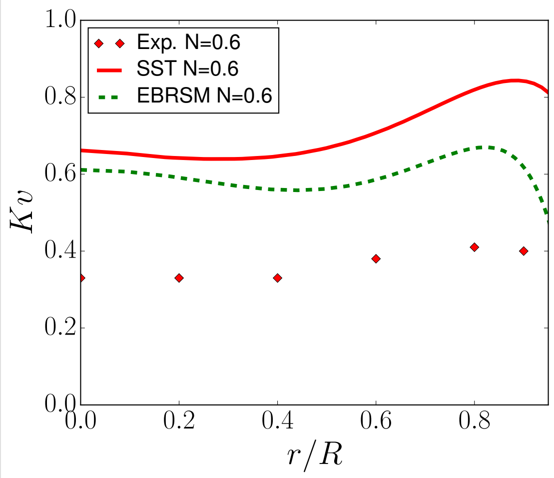


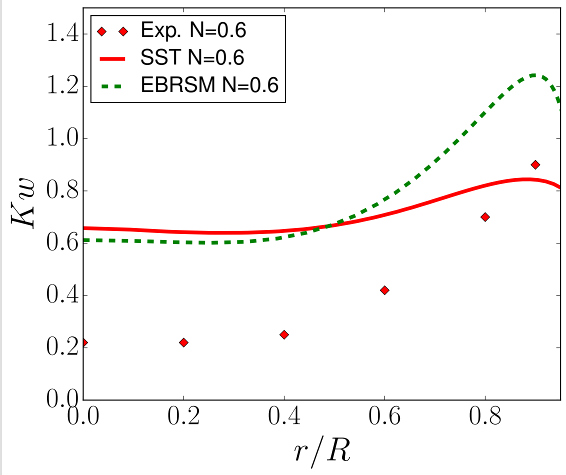
Includes Richardson correction- will be shown later how important this is

- Similar trends to previous work of Poroseva et al. (2002) also using a RSM

Results

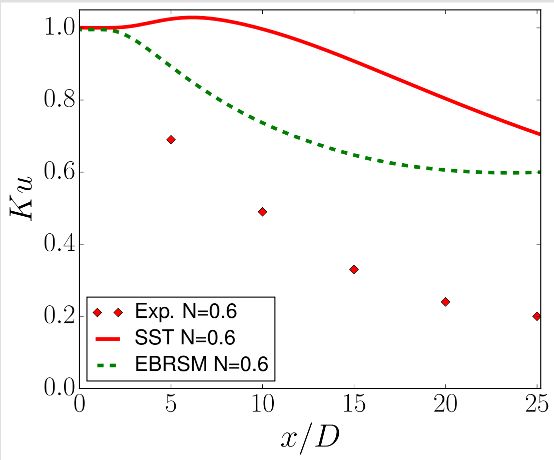


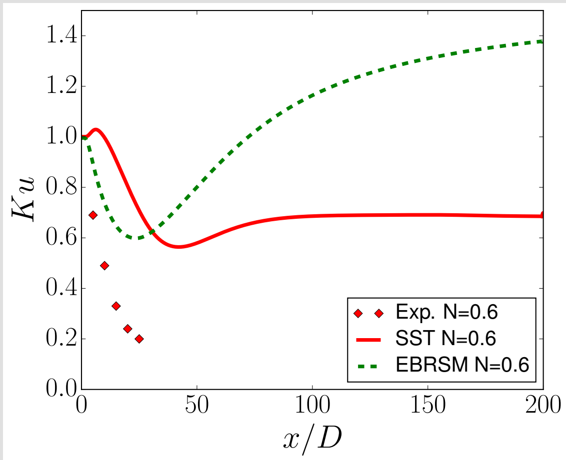


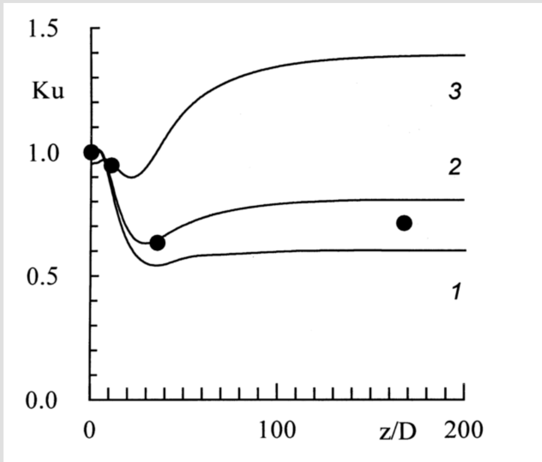


- Turbulent suppression is under-predicted by both models
- Closer agreement with RSM – better able to capture anisotropy

Results – long pipe







Poroseva et al. (1999), N=0.5, r/R=0, three RSM variants

- Experimental data is for the short pipe (50D) but real interest is the full pipe at 200D
- Studied by Nishibori et al. (1987) but limited comparative data
- Shown here at r/R=0.6
- Interesting sensitivity to the turbulence recovery, also observed in Poroseva et al.

Results - Rotation correction

Previous studies (not all) have shown that it is necessary to have some sort of correction in the dissipation equation to account for rotation

Popular approaches have been Richardson correction as originally shown by Bradshaw and later Launder but these were co-ordinate dependent.

Spalart/Shur developed popular correction that is co-ordinate independent but partly for ease of implementation we assess the work of Hellsten (1998) who developed a simpler correction function.

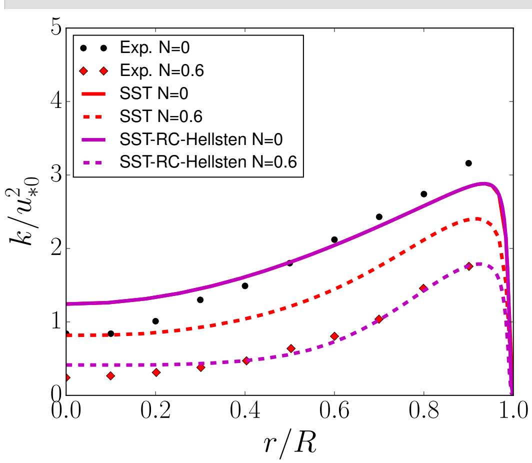
SST: Modifies the destruction term in omega – C_{rc}=1.4

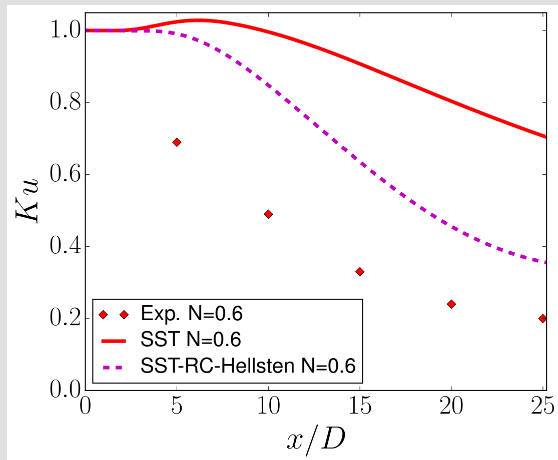
EB-RSM: Modified destruction term in epsilon – C_{rc} = 0.8

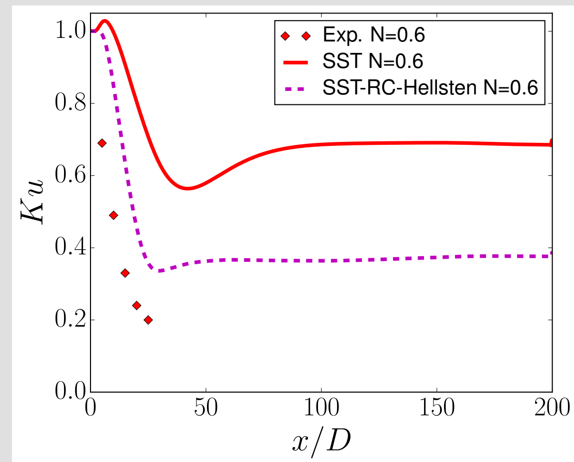
$$Ri = \frac{|\Omega_{ij}|}{|S_{ij}|}\left(\frac{|\Omega_{ij}|}{|S_{ij}|} - 1\right)$$

$$F_{rc} = \frac{1}{1 + C_{rc} Ri}$$

Results

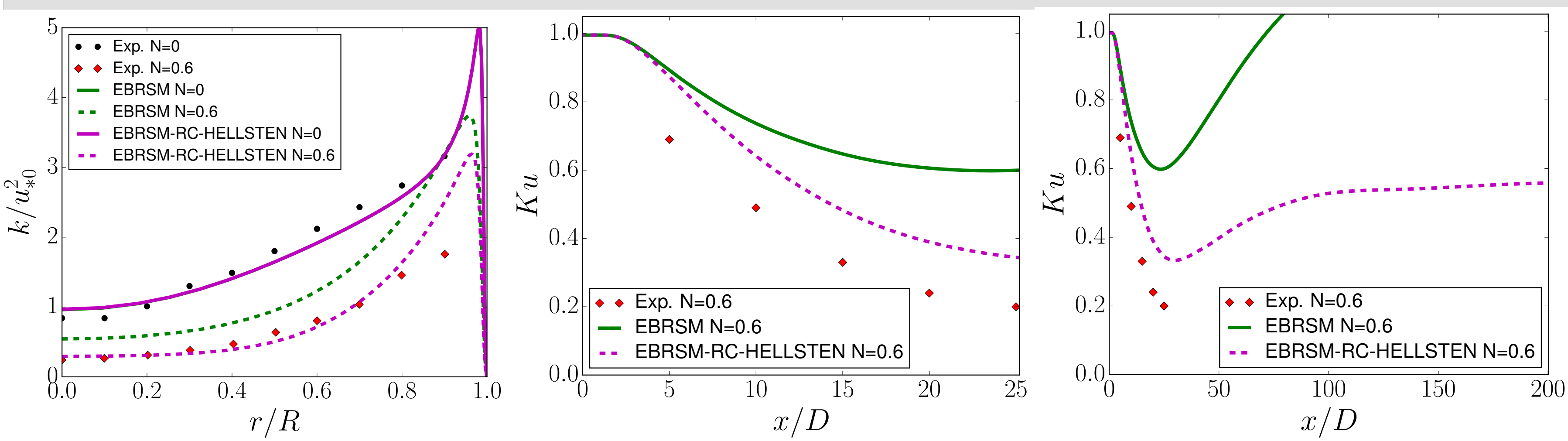






- Noticeable improvement for the SST model with the correction
- Found the updated coefficient C_{rc}=1.4 better than original 3.6 (as noted on NASA TMR site)
- Still unable to match turbulence suppression – inability to explicitly account for rotation and anisotropic effects

Results



- Similar improvement for EB-RSM
- Brings it much closer to the previous work of Poroseva and others
- Still using Daly-Harlow turbulent diffusion model which has been found to be inferior to others for this test-case
- Question of tuning.. Needs wider validation

Future Work

- Evaluate more advanced turbulent diffusion models
- Validate rotation correction over a wider range of flows
- DNS/Exp for longer pipe
- How can we relate this to a wing-tip vortex?

Conclusions

- V&V of turbulence models in OpenFOAM
- Interesting rotation test case to test turbulence models
- RSM vs. SST surprisingly close with rotation correction
- Future work needed to further analyse data

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Thank you

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